Simulation of Heat and Mass Transfer during Artificial Ground Freezing in Saturated Saline Groundwater

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Abstract: Artificial ground freezing (AGF) method, implemented in coastal areas or artificial islands, will inevitably face saline groundwater environment which will have an effect on the soil freezing process. In this paper, based on the theory of heat and mass transfer with phase change in porous media, a fully coupled COMSOL Multiphysics® model with solute transport and artificial freezing temperature field is established. This model simulates the salt concentration and temperature distribution during the freezing process. Through case studies, the evolution rule of frozen barrier under with variable salinity is summarized. The results indicate that the solute migrates from the frozen zone to the unfrozen zone during freezing. With increasing concentration, the freezing fringe gradually shrinks and the frozen barrier thickness decreases linearly. The higher the ambient concentration is, the less obvious the salt migration can be expected.

Keywords: Artificial ground freezing method, saline groundwater, freezing point, solute exclusion, frozen barrier.

1. Introduction

With increasing demand of good water barrier and non-pollution characteristics, artificial ground freezing (AGF) method is particularly widespread in environmental engineering (containment of hazardous waste), mining engineering (mine excavation), and especially in underground engineering in coastal area. However, in coastal area, there are some special environmental and geological problems, such as seawater intrusion. These problems will lead to an increasement in groundwater salinity. Engineering experience shows that the presence of salts in groundwater has a negative impact on the construction of artificial freezing: it will reduce the frozen wall thickness and drastically alter the mechanical properties of frozen soils. In order to further improve the reliability of AGF application in the coastal area, we focus on the numerical simulation of artificial frozen barrier evolution in saturated saline groundwater in this study.

The migration of salt during the soil freezing process is a complex process. It commonly consists of salt rejection and brine drainage from an extended partially frozen region (Baker and Osterkamp, 1989). Owing to the inability of ice crystals to incorporate most alien molecules, the ice grows only by association with water molecules. This self-purification effect results in the solute exclusion from the phase change zone. Eventually, an unstable “high salt concentration zone” will form near the freezing fringe.

Diffusion due to the concentration gradient is one of the determining factor of solute transport. Because the purification effect of ice causes gradual increasement of pore water concentration in frozen area, solute will penetrate the freezing fringe and mixed rapidly in the unfrozen region. Konrad and McCammon (1990) performed a one-dimensional constant end plate temperature test on a saturated clayey silt column. The results indicated that cooling rate is one of the main factors that dominates the solute partitioning, 3 ℃/d is the threshold rate above which no solute are rejected from ice matrix, as for smaller than 0.1 ℃/d, more than 90％ of the solutes will be rejected.

In addition, according to the research of Arenson and Sego (2004) in the coarse sand under controlled freezing gradients and salinities, the difference in thermal conductivity between the soil particles, ice and water will lead to the pockets of unfrozen water with a much higher salt concentration, which will be trapped in the pores. These salts will eventually crystallize when the solution in the pores reaches saturated status.

Some other scholars (e.g. Bing and He, 2008) also focus on the experimental study of salt migration during unidirectional freezing of soil column. Their results imply that the migration of salt plays a more important role in the evolution of frozen barrier than many other factors.

In order to further study the migration process of salt in freezing soil, numerical simulation is often utilized as an efficient method. In porous media, the AGF process in saline groundwater environment can be described by the mathematical model of heat and mass transfer. Panday (1991) and Sheshukov and Egorov (1998, 2002) simulated brine movement during saline soil freezing by using distinct numerical iteration method. On the one hand, due to the presence of salinity, salt water freezing point which is the key factor controlling the phase change and the mass and heat transfer will be affected by the salt concentration. On the other hand, freezing point controls the location of freezing fringe. At the freezing fringe where the salt concentration will enrich, a redistribution of concentration will be resulted.

In this paper, the intent is to establish a fully coupled numerical model for salt concentration and freezing temperature field. Based on this model, an AGF engineering project in saturated saline groundwater was simulated and the evolution rule of frozen barrier was analyzed.

2. Method and governing equations

The process of soil freezing is characterized by pore water crystallization in the soil. Due to the surface energy of the soil particles, a certain amount of water adsorbed on the soil particles will not freeze, i.e. unfrozen film water. As the temperature decreases to freshwater freezing point, pore water begins to freeze accompanying by the migration of salt. Depending on the freezing rate, soil type, initial concentration and other factors, a portion of the brine will be drained into the unfrozen zone and the remaining will be trapped in the pore. This results in a high salt concentration in the unfrozen water core. The component diagram of freezing soil in saturated saline groundwater is shown in **Figure 1**.

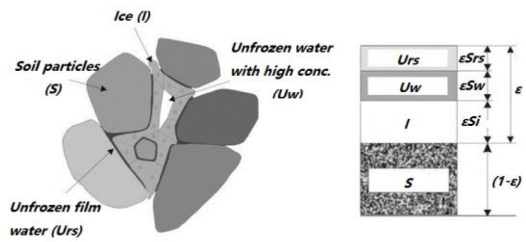


Figure 1. Component diagram of freezing soil in saturated saline groundwater.

Based on the above introduced physical process, several simplified assumptions are introduced to facilitate the research work as follows:

(1) The soil matrix is non-deformable and the ice is incompressible;
(2) The soil materials is homogenous and isotropic;
(3) Convective heat and mass transfer can be ignored;
(4) Moisture migration under the temperature gradient is negligible; salt in porous media is evenly distributed.

2.1 Freezing temperature curve

The presence of salt lowers the freezing point of the saline groundwater, which in turn affects the process of soil freezing. The relationship between the freezing point depression and concentration can be obtained from the Clausius-Clapeyron equation. In this paper for simplification, we assume a linear dependence of temperature on concentration by the following equation:

$$\rho_w \frac{L}{T_0}(T_f - T_0) + RT_0 c = 0 \tag{1}$$

where T_f and T_0 are the freezing point of the salt-mixed water solution and pure water, respectively; c denotes the concentration of solution; R is the universal gas constant. The curve of freezing temperatures of variable concentrations are shown in **Figure 2**.

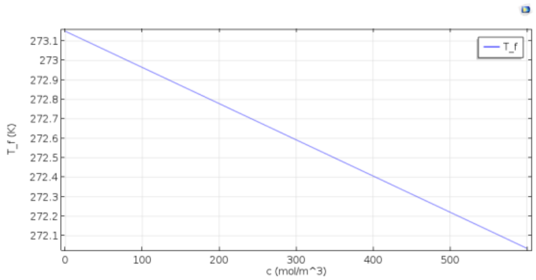


Figure 2. Freezing temperatures of various concentrations.

2.2 Unfrozen water content

According to the component diagram (**Figure 1**), unfrozen water contains two kinds of unfrozen water: the "unfrozen film water" (U_{rs}) which will not freeze and and the "unfrozen water with high concentration" (U_w). The latter one is strongly dependent on the freezing temperature near which the phase change will occur.. This means that the pore space is saturated with unfrozen water and/or ice. Thus, the saturation of the unfrozen water in the pore space can be described by the following sigmoid function:

$$S_w = (1 - S_{rs}) / (1 + a \exp(T - T_f)) \quad (2)$$

where S_w and S_{rs} denote the saturation degrees of U_w and U_{rs}, respectively. The saturation of ice S_i equals to 1- S_w - S_{rs}; a is the transition interval factor which can be used to adjust the radius of phase change region.. The S_w and its derivetive with respect to T curves at c=600mol/m^3 are shown in **Figure 3**

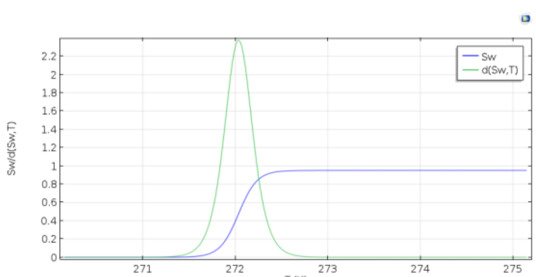


Figure 3. S_w and its derivetive d(Sw,T) with respect to T curves at c=600mol/m^3

2.3 Governing equations

Based on the theory of heat and mass transfer with phase change in porous media, soil freezing process in saturated saline groundwater will be presented by employing the conservation of mass for solute and the conservation of energy .

The governing equation for solute transport in the liquid phase as,

$$\varepsilon \frac{\partial S_w c}{\partial t} - \nabla[\varepsilon S_w D \nabla c] = Q_c \quad (3)$$

where ε is the porosity; D is the diffusion coefficient; Q_c is the concentration source or sink.

The governing equation of freezing temperature field for the system as,

$$C_{eq} \frac{\partial T}{\partial t} - \nabla[\lambda_{eq} \nabla T] - \rho_w L \frac{\partial S_w}{\partial T} = Q_T \quad (4)$$

where C_{eq} and λ_{eq} are equivalent to volumetric thermal capacity and bulk thermal conductivity (calculated by a typical representative volume element (RVE) method), respectively; $-\partial S_w / \partial T$ is the solid fraction, which is equal to the derivative of S_w with respect to T .

3. Use of COMSOL Multiphysics® software

With the simulation software COMSOL Multiphysics®, a full coupling of heat and solute transport by combining physical interfaces (modules) of Coefficient From PDE and Transport Diluted of Species in Porous Media is established. Firstly, by defining variable freezing temperature T_f, the caculated concentration result will be coupled to the temperature field at each time step. The concentration-dependent freezing temperature, in turn, controls the location of the freezing fringe, resulting in concentration enrichment and diffusion.

In this work, the purpose is to simulate a 2D AGF engineering (Hu and Liu (2016)) in saturated saline groundwater. In order to verify the capacity of solute exclusion and phase change of this model, a geometric model of only two freezing pipes is selected as a first step. The pipe sapcing is 1.1m and pipe radius is 0.05m. Other parameters are consistent with the former

AGF engineering case study of Hu and Liu (2016).

The concentration distribution curves of the unfrozen zone ($T > T_f$) on the center line of these two pipes at various time are shown in **Figure 4**. The result shows that the freezing fringe gradually progresses to the center and the concentration continues to accumulate in unfrozen zone along with the soil freezing. Temperature vs. time curves at various concentrations at the midpoint are shown in **Figure 5**. This result indicates that due to the release of latent heat of phase change, the temperature of the soil decreases slowly in the vicinity of 273.15K. Below this temperature, the difference in freezing rate at various concentrations gradually appears.

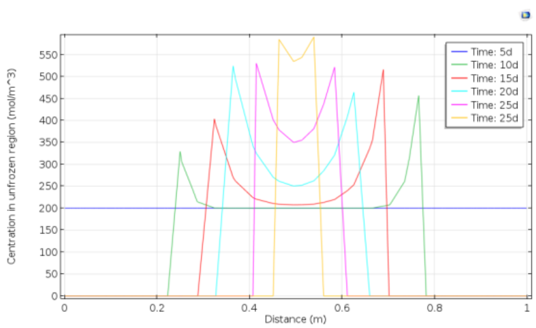


Figure 4. Concentration distribution curves of the unfrozen zone ($T > T_f$) on the center line at various time (initial concentration is 200mol/m^3).

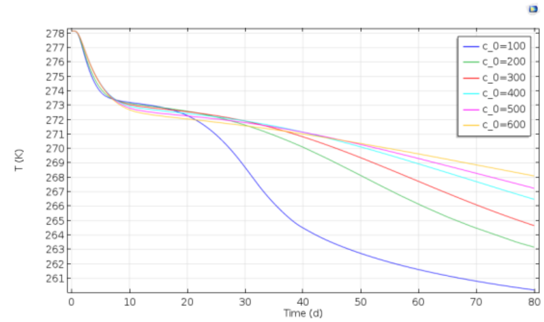
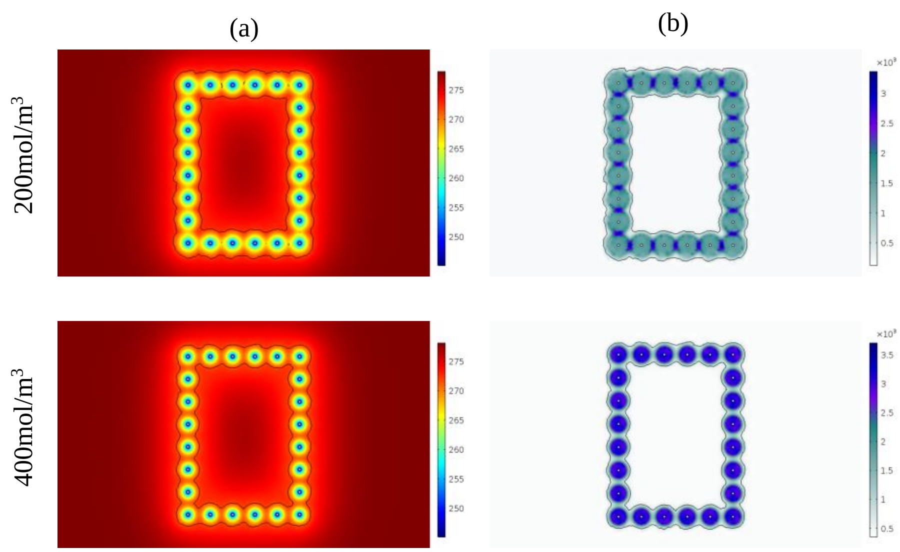


Figure 5. Temperature vesus time curves at various concentration at the midpoint.

After the initial validation of this model, based on the AGF model of Hu and Liu (2016), the effect of groundwater salinity on the evolution of frozen wall is further discussed.

4. Result & Discussion

As the main solute component of seawater is NaCl, the upper limit of groundwater salinity in seawater intrusion area has an average salinity of seawater, i.e. 35ppt (ca. 600mol/m^3). In this work, in order to investigate the effect of salinity on the evolution of freezing barrier, the distribution of soil temperature and solute concentration at various groundwater salinity (200mol/m^3, 400mol/m^3, 600mol/m^3) was simulated. The result is shown in **Figure 6**.



600mol/m^3

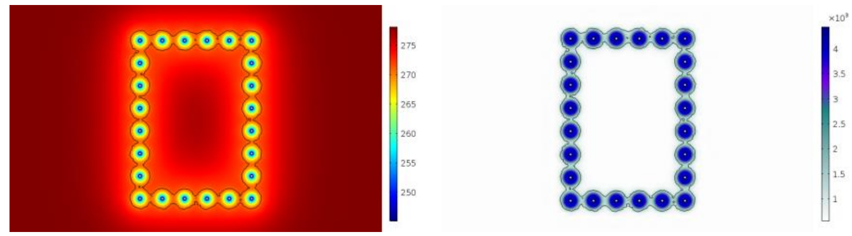


Figure 6. The distribution of soil temperature (a) and solute concentration (b) at various groundwater salinity (200mol/m^3, 400mol/m^3, 600mol/m^3) on the 40th day

Temperature distribution maps (**Figure 6(a)**) show that the freezing fringe (black solid line) continue to shrink with the increasing salinity. This indicates that the thickness of the frozen barrier will decrease as the concentration increases. In **Figure 6(b)**, the concentration of migration presents a different characteristic. When the ambient concentration is low (200 mol/m^3), the concentration enrichment area is between each adjacent pipes. When the ambient concentration is high, a large amount of solute is trapped around each pipe.

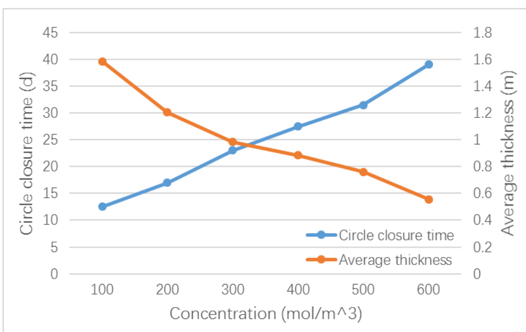


Figure 7. Circle closure time of freezing barrier (left y-axis) and average thickness (right y-axis) of frozen barrier evolution at various concentration..

Figure 7 shows the circle closure time and average thickness of frozen barrier evolution at a concentration from 100 to 600 mol/m^3. These two curves indicate that with the increasement of the ambient salinity the circle closure time extends linearly and average thickness gradual reduces. The rate of time extension and thickness reduction is about 0.05d and 0.02m per mol/m^3, respectively.

5. Conclusions

With COMSOL Multiphysics®, a fully coupled model of concentration and temperature in saturated saline groundwater was initially established. Solute exclusion and phase change during freezing are considered. During freezing the solute migrates from the frozen zone to the unfrozen zone. With increasing concentration, freezing fringe gradually shrinks. The difference in the ambient concentrations governs the rule of solute transport. The salt is enriched between each adjacent pipes with low ambient concentration and trapped around each pipe with high ambient concentration. With increasing ambient concentration, the circle closure time of the freezing barrier extends linearly and its average thickness gradual reduces. It implies that the higher the ambient concentration is, the less obvious the salt migration is to be expected.

In the next step, we will focus on field experimental research for this issue. The effect of groundwater salinity on the frost heave problem during the freezing process will also be a main research interest.

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